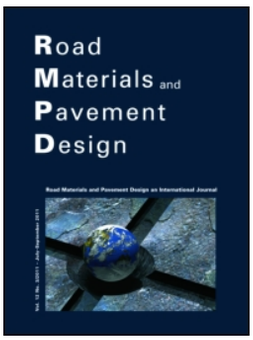

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New Test Protocol to Measure Fatigue Damage in Asphalt Mixtures

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ABSTRACT. *The measurement, analysis and interpretation of hot-mix asphalt concrete fatigue tests have been a subject of research for many years. Standard flexural tests using ectangular or trapezoidal beams are non-homogeneous in that the stress-strain fields and the temperature distribution within the test specimens are unknown, making a rigorous analysis of the phenomena that occur during these tests very difficult. A new protocol for fatigue testing is proposed using a uniaxial "push-pull" test with three loading stages on a cylindrical specimen. The first and last stages are at very low loading levels, below the endurance limit of the mixture being tested. Fatigue damage occurs during the second stage of loading when the applied stress or strain is sufficient to cause fatigue damage. The difference between the moduli at the end of the first and at the end of the third stage of loading is caused by fatigue alone. The presence of an endurance limit is verified and it is shown that the drop in modulus during a standard fatigue test is primarily caused by nonfatigue phenomena. The rate of fatigue damage obtained with the proposed protocol is approximately one tenth of that predicted by standard tests. The effects of non-fatigue phenomena such as self heating, self cooling, and nonlinearity are discussed, as well as a phenomenon that the authors, for want of a better term, refer to as thixotropy. The authors conclude that the major portion of the modulus lost during a fatigue test, as well as modulus gained during periods of rest or decrease of loading, is the result of thixotropy.*

KEYWORDS: *Fatigue, Endurance Limit, Thixotropy, Self Healing, Self Heating, Nonlinearity, Self Cooling, Damage.*

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1. Introduction

How much fatigue damage is caused by N cycles of loading? This question may be easy to answer in the case of some materials such as metals where damage during a fatigue test can be directly related to the change in modulus. In the case of hot-mix asphalt concrete (HMAC) there is no easy and direct answer to this question because of the complicated mechanical behavior of the mixture and the binder. Different laboratory test methods have been used to characterize the fatigue of HMAC, and they are all based in one way or another on the modulus of the HMAC.

A major issue that must be addressed when analyzing HMAC laboratory fatigue data is the contribution of non-fatigue related phenomena to the change in modulus. These phenomena can have a much greater effect on the observed change in modulus than the fatigue damage itself. Previous studies have either ignored the effect of other phenomena on the variation of the modulus or have analytically separated their influence from the damage caused by fatigue [ASH 98, BAA 04, DEL 96, DIB 96, PIA 89].

The test protocol described herein allows a direct measure of the damage caused by fatigue by separating the effects of non-fatigue-related phenomena from the effects of fatigue, experimentally rather than analytically. The purpose of this paper is to present this new fatigue testing protocol and to show and interpret the results of applying this protocol to laboratory mixtures. The paper provides an insight into self healing, self heating and self cooling. The presence of an endurance limit is discussed, and a means for evaluating thixotropy is presented.

2. Previous studies

Many studies have been performed with the objective of establishing a reliable means for predicting in-service fatigue performance from laboratory tests. Still, much is unknown regarding the mechanism responsible for HMAC fatigue behavior. Fatigue testing in the United States is traditionally performed using a four-point bending test (FPBT) as pioneered by Deacon and Monismith [DEA 65]. In Europe the trapezoidal test is also commonly used for fatigue testing. Both test methods may be considered as bending beam or flexural tests. Reviews of flexural and other fatigue tests have been presented in detail elsewhere [BAA 04, DIB 04, FRA 98].

Flexural tests have several disadvantages when a rigorous analysis or modeling of the fatigue process is desired. The stresses or strains in a flexural test specimen are not uniform across its cross-section. In this case the test is often referred to as a non-homogeneous test. With the occurrence of damage in a non-homogeneous test, the stress and strain distributions become nonlinear and the modulus changes disproportionately within the specimen. As a consequence, flexural tests can be neither controlled stress nor controlled strain modes but instead are controlled displacement or controlled load modes. These conditions make a rigorous analysis

of the fatigue process difficult because once fatigue damage occurs, the modulus, stresses and strains are all unknown and vary throughout the specimen in an unknown manner. This inability to conduct fatigue tests in stress or strain controlled mode complicates the development of a fatigue law. Further, relating the laboratory test results to the stresses and strains in the pavement becomes complicated if the stresses or strains in the laboratory test are uncertain and not controlled.

Uniaxial fatigue testing of cylindrical specimens has been used by a number of researchers as an alternative to flexural testing. Uniaxial fatigue testing was performed by Lytton and his coworkers during the Strategic Highway Research Program (SHRP) [LYT 93] and this work was extended by Kim and others [KIM 97, LIT 99]. In Europe, uniaxial fatigue testing with a more sophisticated test configuration (when compared to earlier studies [AGU 81]) has been promoted by Di Benedetto and his coworkers [BAA 04, DIB 96]. In theory, the main advantage of a uniaxial test is that a homogeneous stress and strain field is established in the middle portion of the test specimen. In practice sufficient specimen length to height ratio should be considered so that in the middle portion of the cylindrical specimen the stress and strain are as close as possible to a uniform distribution [WEI 99]. Homogeneous testing allows the test to be controlled in stress or strain mode. A homogeneous test is also easier to model and analyze, allowing the merger of controlled stress and controlled strain testing so that the two loading modes may be represented by a single relationship [ASH 98, BAA 04, DIB 96].

Another problem that has drawn considerable attention is the definition of the point in the test at which failure occurs. Fatigue failure is not a spontaneous event; it must be defined by some reliable and easily applied method. Researchers have proposed a wide variety of different failure criteria such as the number of loading cycles at which the modulus is reduced to 50 percent and various criteria based on energy concepts and the change in phase angle [DIB 04, GHU 00, PRO 97, ROW 00]. However, there appears to be universal agreement that fatigue proceeds in three distinct phases [BAA 04]. (Note: The term “Phase” as used in the literature is not to be confused with the term “Stage” that is used later in this paper.)

In Phase I the modulus loss is due to fatigue damage and to other non-fatigue effects such as self heating. During this phase, the modulus decreases exponentially, eventually slowing to what appears to be a constant rate of decrease. This linear portion is referred to as Phase II. In fact, the rate of decrease in modulus is not constant during Phase II but decreases at a decreasing rate as Phase II progresses [ASH 98]. The predominant cause of the loss in modulus during Phase II is fatigue, an extension of the fatigue damage that occurred during Phase I. Although fatigue damage is incurred during both Phases I and II, it is largely masked by non-fatigue effects during Phase I. Phase III is characterized by a marked decrease in modulus. Failure in terms of macrocracking and ultimately rupture occurs during Phase III. Phases I and II may also be considered as the crack initiation phase (microcracking) and Phase III as the crack propagation phase (macrocracking) [DIB 96, LIT 99].

Two behavioral patterns are of interest: the sudden and relatively large drop in modulus that occurs at the beginning of Phase I and the healing that occurs in tests with rest periods. Self heating is responsible for a part of the sudden drop in modulus during Phase I [DIB 96, PIA 89] while self cooling is partly responsible for the recovery of modulus during rest periods [RIV 97]. The term self cooling, while appearing to be incongruous, simply refers to the reduction in specimen temperature that results from the reduction in dissipated energy when the applied load is reduced. It is well known that self healing can significantly extend the fatigue life of HMAC [BON 82, BRE 05]. This behavior is attributed to the repair of damage and was studied extensively by Lytton *et al*. during SHRP [LYT 93]. More recently, Little *et al*. have applied continuum damage models and healing concepts to explain the recovery in modulus [LIT 99].

The presence of an endurance limit has not been verified for HMAC. If an endurance limit exists and if pavements can be designed so that the stresses are below the endurance limit, the pavement will theoretically never incur fatigue damage. Monismith *et al*. "…assumed that the strains less than $70x10^{-6}$ in. per in. would cause no fatigue damage," implying that an endurance limit may exist at 70 μ-strain [MON 71]. Carpenter *et al.* recently concluded that an endurance limit does exist and is in the range of 70 to 90 μ-strain at 20°C 10 Hz [CAR 03]. Based on a damage analysis of experimental results, Ashayer postulated the presence of an endurance limit for two mixtures tested at 10°C and 10 Hz [ASH 98]. He estimated endurance limits of 30 and 80 μ-strain for the two mixtures that contained unmodified binder and modified binder, respectively. In spite of the above observations, there is no conclusive evidence to verify an endurance limit for HMAC. This issue is currently being addressed in the United States in National Cooperative Highway Research Program (NCHRP) Project 9-38, "Endurance Limit of Hot-Mix Asphalt Mixtures to Prevent Fatigue Cracking in Flexible Pavements."

3. Proposed test protocol

The proposed test protocol consists of three consecutive stages of sinusoidal loading centered at zero stress (or strain) applied to a cylindrical test specimen. The stages are similar except for the amplitude of loading and the number of loading cycles in each stage. These three stages are:

– Stage I, during which the loading is below the endurance limit.

– Stage II, during which the endurance limit is exceeded.

– Stage III, during which the loading is the same as Stage I.

The difference in modulus at the end of Stage I and Stage III (difference in the two asymptotes) is assumed to be equal to the total damage caused by fatigue during Stage II. This is shown schematically in Figure 1. A significant difference in the proposed protocol from those used in classical fatigue studies is that three successive loading stages are applied. As discussed below, a number of phenomena are

operative during the various stages of loading. These include transient effects, self heating, self cooling, nonlinearity, and a reversible loss in modulus that the authors, for want of a better term, refer to as thixotropy. Although a multitude of definitions for thixotropy appear in the literature the author's usage is in keeping with a general definition given by Bauer and Collins: "When a reduction in magnitude of rheological properties of a system, such as elastic modulus, yield stress, and viscosity, for example, occurs reversibly and isothermally with a distinct time dependence, the system is described as thixotropic" [BAU 67]. Others have also used the term thixotropy in conjunction with fatigue of HMAC [ASH 98, BAA 04, BOD 03, BRE 05, DEL 96, DIB 04].

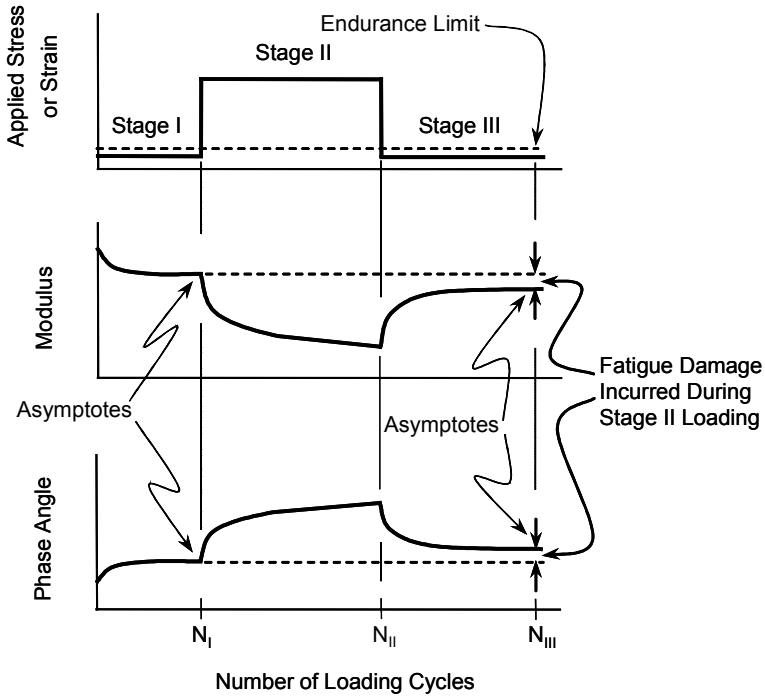

Figure 1. *Schematic of loading in Stages I, II, and III*

3.1. *Stage I*

In this stage the amplitude of loading is below the endurance limit of the test specimen so that the loading does not cause fatigue damage. In Stage I, the test can be carried out in either a strain or stress controlled mode. At the beginning of Stage I a very intriguing phenomenon occurs. Despite the fact that the loading is below the

endurance limit of the specimen, the modulus decreases from the very first cycle and continually decreases with the number of loading cycles until it reaches an asymptote, as shown in Figure 1. Because the loading is below the endurance limit of the test specimen, by definition this decrease in modulus cannot be the result of fatigue damage. The phenomena that may be involved in this drop of modulus are discussed below.

3.1.1. *Self heating*

The effect of self heating on the decrease in modulus observed during Stage I is not ignored in this paper but is considered to be very small compared to the effect of other non-fatigue related phenomena. The dissipation of energy and resulting self-heating, which lowers the modulus, cannot fully account for the loss in modulus, because the loss in modulus is much greater than what can be attributed to the increase in temperature. Similarly, the rate of the initial decrease in modulus cannot be explained by self heating when the rate of heat transfer is considered [ASH 98]. Based on the temperature measurements made during this study, self heating was not detected on the specimen surface during Stage I. Given the precision of the equipment used in this study, as well as some analytical calculations, if there is any self heating on the specimen surface it is less than 0.01°C in Stage I. This is discussed in more detail later in this paper.

3.1.2. *Thixotropy*

During Stage I thixotropy causes a sudden and relatively large decrease in the modulus of the mixture followed by a decrease in the rate of change until the modulus approaches an asymptote. As the asymptote is approached, the specimen is in an isothermal condition, and thixotropy and self heating no longer contribute to modulus decrease. Stage I, where the stresses and strains are by definition below the endurance limit of the test specimen, provides a direct means for measuring the effects of thixotropy on the specimen modulus.

3.1.3. *Termination of Stage I*

The exact number of loading cycles required to define Stage I cannot be predefined but must be determined experimentally as the point in time where dE/dN (variation of modulus versus number of cycles) approximates zero. A sufficient number of loading cycles must be applied to verify that an asymptote has been reached. Since the loading is below the endurance limit, additional loading cycles cause no harm to the test specimen, other than needlessly extending the test time. Once the mixture has reached an equilibrium condition as evidenced by the asymptote ($dE/dN \approx 0$), Stage II is initiated without interruption or rest.

3.2. *Stage II*

The test mode (strain or stress control), the amplitude of loading and the total number of cycles in Stage II are determined by the query: *How much fatigue damage is caused by N cycles of loading?* Fatigue damage is expected in Stage II because the amplitude of loading is above the endurance limit. During Stage II, phenomena that contribute to the variation of modulus are transient effects, thixotropic behavior, energy dissipation (heat generation) and fatigue damage. Furthermore, any nonlinear behavior should be taken into account if the strain amplitude exceeds the limit of linearity. The influences of these phenomena on the modulus variation in Stage II are discussed below.

3.2.1. *Transient effects*

When loading is first applied to a test specimen or when there is a discontinuity in the loading pattern, transient effects can occur. These effects can be the result of specimen and machine inertia, machine compliance, and the operating characteristics of the testing machine and data acquisition system. This requires a careful consideration of data immediately after a change in loading so that the transient effects are identified as artifacts and not interpreted as material response.

3.2.2. *Thixotropy behavior*

Because of the increased loading at the beginning of Stage II the effect of thixotropy on the modulus and phase angle is observed immediately. This causes a drop in the modulus and an increase in the phase angle similar in form, but much greater in magnitude, to the variations that occurred during Stage I.

3.2.3. *Dissipated energy*

The increase of loading amplitude in Stage II increases the dissipation of energy (constant at the end of Stage I) which in turn increases the specimen temperature. This increase in specimen temperature causes a measurable decrease in the modulus of the test specimen during Stage II. The temperature measurements on the surface of the specimen during Stage II are given later in this paper. A rise in temperature lowers the modulus and increases the phase angle. Changes in the modulus and phase angle in turn modify the rate of energy dissipation. As a result, the pattern of self heating depends upon whether the test is conducted in a controlled stress or controlled strain mode. The proposed protocol takes into consideration the effect of self heating regardless of the test mode.

3.2.4. *Fatigue damage*

Because the amplitude of loading in Stage II is greater than the endurance limit of the test specimen, each cycle of loading causes some amount of fatigue damage to the specimen. Consequently, during each cycle part of modulus change is caused by

fatigue. The challenge of this test protocol is to determine how much of Stage II modulus change is due to fatigue damage.

3.2.5. *Nonlinear behavior*

For the sake of simplicity, the behavior of HMAC is often assumed to be linear when strains are somewhat below 100 μ-strain [DIB 04, DOU 95]. However, it is very common to exceed this limit during laboratory fatigue testing. The effect of nonlinear behavior is to decrease the modulus of material and increase the phase angle as the strain increases. In contrast to a strain controlled test, in a stress controlled test the amplitude of strain increases with the number of loading cycles which in turn increases the effect of nonlinear behavior. If the material response is nonlinear during any part of Stage II, a part of modulus decrease must be attributed to nonlinearity.

3.2.6. *Termination of Stage II*

In Stage II, loading is applied until the predetermined number of loading cycles in the query is reached. It is important that the number of loading cycles does not reach the point where macrocracking occurs. Accounting for the complications of specimen macrocracking is beyond the scope of the protocol and this paper. The onset of macrocracking can be easily detected by comparing the values recorded by the three displacement transducers. At the onset of macrocracking the values start to diverge [ASH 98]. The loading for Stage III starts at the end of Stage II without any interruption or rest period.

3.3. *Stage III*

In Stage III the amplitude of the loading is returned to the amplitude used in Phase I (below the endurance limit) resulting in a sudden decrease in the loading amplitude at the beginning of Stage III. The resulting change in modulus is counterintuitive. Despite the continuous loading, the specimen modulus increases suddenly and continues to increase at a decreasing rate as the number of loading cycles increases. The increase in modulus continues until an asymptote is reached. It is very important to emphasize that the increase in modulus in Stage III occurs without any rest in the loading or change in the controlled temperature. The part of the modulus that is not recovered in this Stage is attributed solely to the fatigue damage that was incurred during Stage II. In Stage III no fatigue damage is incurred because the amplitude of loading is below the endurance limit of the test specimen. In addition the authors assume that no healing takes place during Stage III since the specimen remains under continuous dynamic loading. The phenomena that contribute to the change in modulus are thixotropy and self cooling. If the strain at the end of Stage II is in the nonlinear region, nonlinearity should be also taken into account. These phenomena and their effect on modulus are discussed below.

3.3.1. *Thixotropy*

With the sudden loading decrease at the beginning of Stage III the effect of thixotropy behavior is to increase the specimen modulus, with its highest rate of increase occurring at the beginning of Stage III. This rate slows with the number of cycles and eventually becomes nil as the modulus attains an asymptote. When this equilibrium is reached thixotropy no longer has an effect on the specimen modulus.

3.3.2. *Self cooling*

The reduced loading in Stage III decreases the amount of energy dissipated during each loading cycle. As a result, the specimen self cools, and a drop in specimen temperature is observed. This self cooling is reflected in an increase in the modulus. The effect of self cooling on the increase in modulus is more pronounced at the beginning of Stage III. After some number of cycles a new equilibrium temperature, very close to that of Stage I, is established within the specimen. Self cooling no longer causes a modulus change once temperature equilibrium is reached.

3.3.3. *Linearity*

The strain during Stage III is below the endurance limit of the test specimen. At this very low strain the specimen is assumed to behave as a linear viscoelastic material. If, at the end of Stage II, the strain is in the nonlinear region then a sudden change from nonlinear to linear behavior occurs at the beginning of Stage III, causing an immediate increase in the specimen modulus. Note that there is a key difference between the effect of nonlinearity on the increase of modulus compared to that of thixotropy and self cooling. The shift to linear behavior response results in an immediate response from the specimen, but thixotropy and self cooling require a considerable number of cycles of loading to reach equilibrium.

3.3.4. *Termination of Stage III*

The loading in Stage III is terminated when no further increase is observed in the modulus and an asymptote is reached ($dE/dN \approx 0$). With the identification of a definite asymptote at the end of Stage III, the test protocol is terminated, and the total amount of damage by fatigue can be calculated. In Stage III the minimum number of loading cycles to reach and identify the asymptote cannot be predefined. Therefore, the point where an asymptote is reached can only be determined by observing the response of the test specimen. For instance, at 10°C and 10 Hz, the test may require several hundred thousand loading cycles to attain an asymptote in Stage III.

3.4. *Fatigue damage*

At the end of Stage III the specimen conditions are similar to those existent at the end of Stage I. By the end of Stage III, the effects of non-fatigue phenomena (self cooling, self heating, thixotropic behavior and material nonlinearity) have been erased. If no damage was incurred during Stage II, the specimen modulus must be the same at the end of Stages I and III. Because damage is incurred only during Stage II, the difference in the moduli at the end of Stages I and III is attributed entirely to fatigue.

3.5. *Summary of proposed test protocol*

In the proposed protocol three stages of loading are applied. In Stages I and III the loading is below the endurance limit, whereas the endurance limit is exceeded in Stage II. The protocol allows a direct measurement of fatigue damage incurred during Stage II, which in terms of modulus is equal to the difference in modulus at the end of Stages I and III. The protocol is summarized in Table 1.

Table 1. *Summary of the test protocol*

	Stage I	**Stage II**	**Stage III**
Applied loading	Below the endurance limit	According to query - can be combination of different loading types	Same as Stage I
Number of loading cycles	Until an asymptote is reached: $dE/dN \approx 0$	According to query but not sufficient to cause macrocracking damage	Until an asymptote is reached: $dE/dN \approx 0$
Test mode	Either stress or strain controlled	According to query - can be any mode or even a combination of different modes	Same as Stage I
Phenomena potentially responsible for change in modulus	Transient effects, thixotropy	Transient effects, thixotropy, fatigue damage, self heating, nonlinearity (depends on strain amplitude)	Transient effects, thixotropy, self cooling, linearity

4. Test equipment, control and measurements

To verify the presence of an endurance limit and to conduct the low-amplitude sinusoidal loading necessary for the proposed test protocol, particular attention was

given to the precision of the loading and the test measurements. Displacement measurements required for calculating the average strain were obtained from three transducers with a gauge length of 75 mm and spaced evenly at 120° on the circumference of the test specimen, Figure 2. One of the transducers was included in the control loop of the testing machine. Software to control the testing machine and provide the data acquisition and analysis was written especially for this study using LabVIEW™. The system allowed sinusoidal tension-compression (push-pull) fatigue testing to be conducted with strain amplitudes as low as 20 μ-strain. Additional details regarding the test apparatus and data acquisition are given elsewhere [SOL 04].

In order to obtain the temperature control precision needed to verify the presence of an endurance limit and to quantify self heating and cooling at low strain amplitudes a dual environmental chamber was used. The testing frame was located within a walk-in environmental chamber, and a small environmental chamber inside the walk-in chamber housed the test specimen. This allowed the temperature inside the internal chamber to be controlled to ± 0.03°C. Nine thermocouples were placed on the surface of the test specimen. Temperature readings were obtained once per minute during the testing.

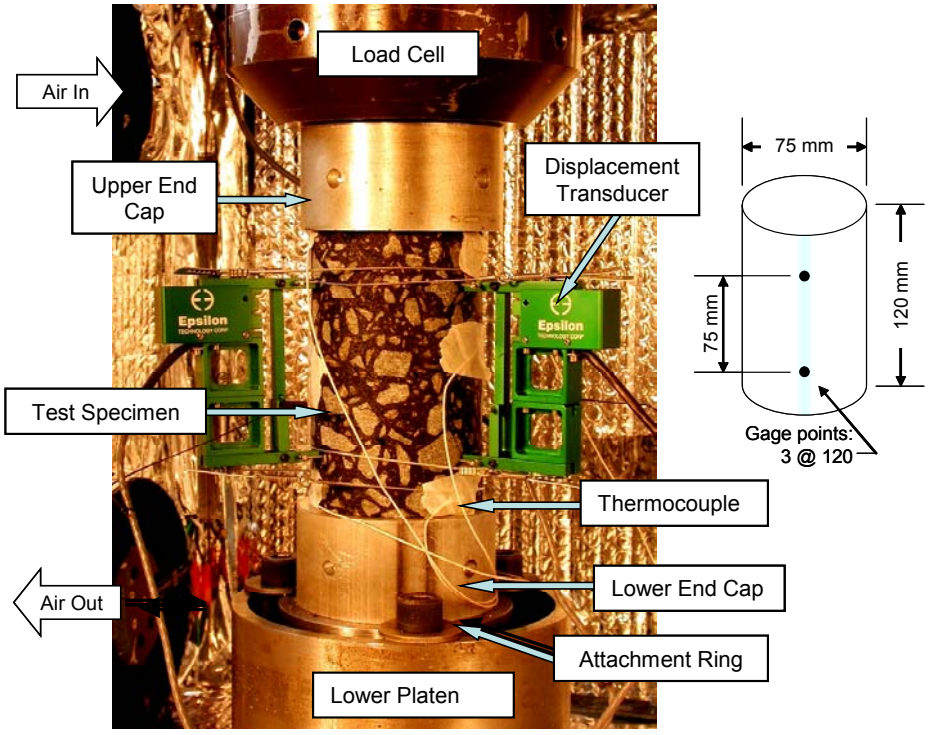

Figure 2. *Test specimen with transducers and thermocouples*

The rate of dynamic data collection was fixed at 1 kHz for each channel. The Levenberg-Marquardt algorithm was used to fit a sinusoidal function to 100 data points per cycle for each channel. From the curve fitting, the measurements of load and the three individual displacements were reduced to values of average axial stress and strain to obtain the specimen average modulus. Phase angle was obtained from the Levenberg-Marquardt algorithm by comparing the measurements from the load and strain control channel. Despite the huge amount of data all the computation was processed in real time [SOL 04].

5. Materials used in study

The test specimens used in this study were taken from an earlier project [SOL 04]. The I-80 and Rt.15 mixtures were sampled in the field from behind the paver during the construction of the wearing courses at test sites for a Pennsylvania Department of Transportation instrumentation study [AND 03]. The AC-5 mixture was prepared at the Federal Highway Administration (FHWA) Turner-Fairbank Highway Research Center (T-FHRC) using aggregates and binder from FHWA Accelerated Loading Studies [STE 00, ROM 00]. All of the mixtures were compacted at the T-FHRC using the French Rolling Wheel Compactor (NF P 98-250-2) to prepare 400 x 600 x 150mm slabs. The compacted slabs were then cut into four rectangular sections from which 75mm diameter by 120mm high cylindrical test specimens were cored, Figure 3. Properties of the mixtures and the binders used in this study are given in Table 2.

Table 2. *Properties of mixtures used in study*

Mixture Property	**Mixture**		
	I-80	Rt.15	AC-5
Mix Type	Superpave 12.5 mm	Superpave 12.5 mm	VaDOT WC-5
Binder Grade	PG 76-22	PG 64-28	PG 58-22
Asphalt Content, %	5.3	5.0	4.8
Air Voids, %[(a)]	6.10	6.70	3.85
[(a)]Average of values measured prior to testing			
Sieve Size, mm	**Gradation, % Passing**		
25.0	100	100	100
19.0	100	100	98.7
12.5	97	93	76.0
9.5	88	84	62.0
4.7	49	53	44.0

2.36	30	35	32.1
1.18	20	22	23.8
0.600	13	15	16.9
0.300	8	10	11.3
0.150	6	6	7.9
0.076	4.2	4.0	5.5

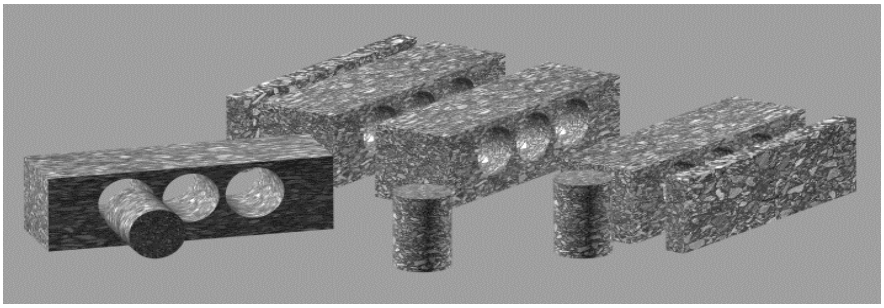

Figure 3. *Cutting and coring of test specimens [ASH 98]*

6. Application of proposed testing protocol to laboratory fatigue testing

All of the testing was conducted in strain control mode with sinusoidal push-pull loading at 10 Hz. The temperature was controlled at 10 ± 0.03°C.

Extensive preliminary testing was conducted prior to the testing reported in this paper to verify the precision of the measurements, to verify the temperature measurements and the self-heating effects, and to establish the presence of an endurance limit. In the preliminary testing, push-pull tests were performed in the controlled strain mode at 20 μ-strains for up to 6,000,000 cycles to verify the existence of an endurance limit. During this testing the presence of an asymptote (in arithmetic axes of modulus versus number of cycles) was observed, providing evidence to the authors' belief that HMAC can exhibit an endurance limit. The slopes of the normalized asymptotes were approximately 10^{-10} indicating that the decrease of modulus was roughly 1 percent every 100,000,000 cycles.

For the purposes of this paper the presence of an asymptote in Stage I was accepted if the normalized slope was approximately 10^{-9} (1 percent every 10,000,000 cycles). This typically occurred long before 1,000,000 cycles of loading were applied in Stage I. It is interesting to note that on the asymptote the variation of modulus is coincident with the variation of the specimen temperature although this is less than ± 0.03°C.

Despite conducting tests with up to 6,000,000 cycles of loading, the presence of an endurance limit for HMCA for engineering application can still be questioned since the heavily trafficked roads are subjected to many more load applications. In theory, the presence of an endurance limit for any material remains limited to the applied number of cycles in the laboratory testing. It should also be pointed out that at the end of Stage I the damage rate, as shown by the assumed asymptote, is so small that it may effectively function as an endurance limit. However, what is very important and supports the authors' assumption in regard to the existence of an endurance limit for HMAC is that the rate of decrease in modulus keeps decreasing during the entire Stage I. Even if a definite endurance limit does not exist for HMAC, since the rate of damage is close to zero and continues to decrease until the end of Stage I, the approach used in the proposed protocol for determination of fatigue damage in Stage II remains valid.

6.1. *Application of protocol to I-80 mixture*

The strain amplitudes used during the testing of the I-80 mixture are reported in Table 3. The average strain in Stage I and Stage III is about 19 μ-strain, which corresponds to a displacement amplitude of about only 1.4 microns. The maximum deviation from the average strain obtained by the three transducers was about 3.7 percent in Stage I and 4.1 percent in Stage III. The average strain in Stage II is about 106 μ-strain with a maximum deviation of 5.2 percent from the average. The small deviations in strains obtained from three transducers verify the assumption that the axial strain can be considered as uniform across the test specimen. Results obtained from the three stages of the test are summarized in Table 4.

Table 3. *Strain amplitudes from three transducers and their average, I-80*

		Transducer			
		1[(a)]	2	3	Avg.
Stage I	Strain amplitude, μ-strain	19.0	18.4	19.7	19.1
	Deviation from average, %	0.4	3.2	-3.7	0.0
	Displacement amplitude, μm	1.42	1.38	1.48	1.43
Stage II	Strain amplitude, μ-strain	104.7	101.8	111.6	106.0
	Deviation from average, %	1.3	4.0	-5.2	0.0
Stage III	Strain amplitude, μ-strain	19.0	18.3	19.8	19.1
	Deviation from average, %	0.3	3.8	-4.1	0.0

[(a)] Used for control

Table 4. *Different parameters measured during the three stages, I-80*

	Initial	Stage I	Stage II	Stage III
Number of cycles	-- --	780,000	300,000	3,240,000
Strain during stage, μ-strain	19	19	106	19
Stress, end of stage, MPa	0.280[(a)]	0.234	1.20[(b)] 1.00	0.227
Modulus, end of stage, MPa	12,430[(a)]	12,220	9,470	11,900
Modulus change in stage, MPa	-- --	-210[(c)]	-2,750	2,430
Asymptote normalized slope	-- --	$2x10^{-9}$	-- --	$9x10^{-10}$
Phase angle, end of stage, °	12.3[(a)]	12.9	19.4	13.6
Dissipat. energy/unit vol., MJ/m^3	4.3	3.1	111.8	3.2
Heating/Cooling, °C	0	0	0.5	-0.5

[(a)] At beginning of Stage I, [(b)] At beginning of Stage II, [(c)] Negative change means loss in property.

6.1.1. *Modulus*

Variations in the modulus versus number of loading cycles during the I-80 test are summarized in Table 4 and shown graphically in Figure 4. In Figure 4 through Figure 6 each curve represents several thousand data points. The strain amplitude in Stages I and III is 19 μ-strain, below the endurance limit of the test specimen as established by an asymptote at the end of Stages I and III. Thixotropy accounts for a 1.7 percent drop in modulus during Stage I. The normalized slope of the asymptote is $2x10^{-9}$ and $9x10^{-10}$ for Stages I and III, respectively. An asymptote is reached at 50,000 cycles in Stage I but only after 2,200,000 cycles in Stage III. During Stage II the applied strain is 106 μ-strain, sufficient to cause fatigue damage to the test specimen. The trends in the data shown in Figure 4 are in agreement with those shown schematically in Figure 1.

In spite of the relatively strong recovery of modulus during Stage III, not all of the modulus is recovered. The difference between the asymptote moduli in Stages I and III, 320 MPa, is the result of fatigue damage. Therefore, the damage caused by fatigue at 10°C and 10 Hz after 300,000 loading cycles with amplitude of 106 μ-strain is only about 2.6 percent of the initial modulus. In a standard analysis, all the modulus lost during Stage II (24 percent) would be attributed to fatigue, roughly nine times the fatigue damage obtained from the proposed protocol [AAS 94]. The standard fatigue analysis cannot account for this difference, nor can it account for the recovery in modulus that occurs during Stage III.

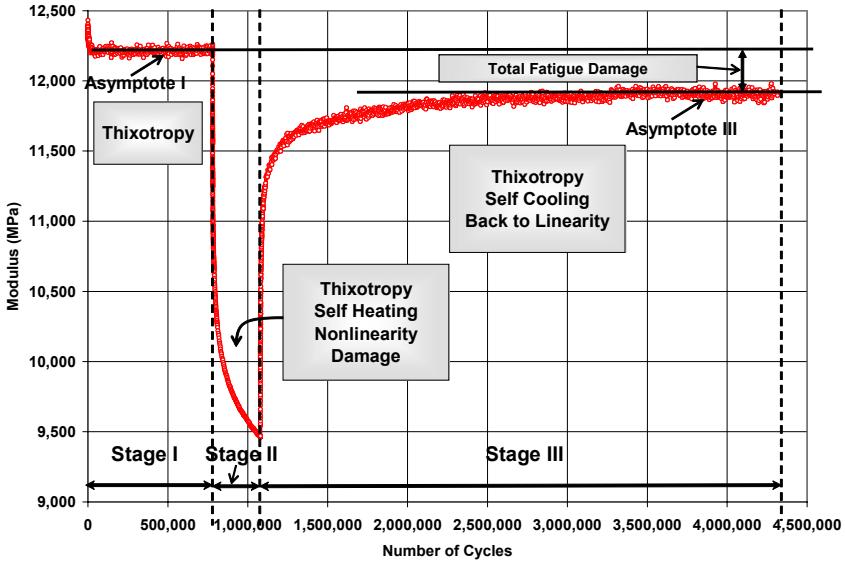

Figure 4. *Modulus* versus *number of loading cycles, I-80*

6.1.2. *Phase angle*

The change in phase angle during the three stages is reported in Figure 5.

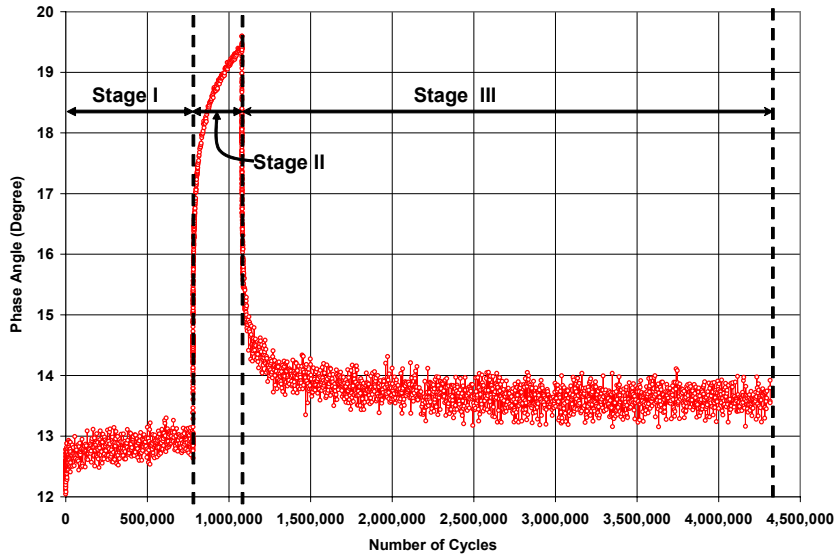

Figure 5. *Phase angle* versus *number of loading cycles, I-80*

Any change in specimen temperature, damage, thixotropy or nonlinearity is reflected as a change in the phase angle as well as a change in the modulus. The nonlinearity, self heating, thixotropy and damage all contribute to the increase in phase angle. The initial phase angle is 12.3 degrees, increases to 12.9 degrees at the end of Stage I and 19.4 degrees at the end of Stage II, and recovers to 13.6 degrees at the end of Stage III. Thus, the increase in the phase angle due to the fatigue damage incurred during Phase II is only about 0.7 degrees (13.6 - 2.9), much less than the 6.5 degrees (19.4 - 12.9) obtained by a standard analysis. The time required to dissipate the effects of thixotropy (reverse) on the phase angle shows a trend similar to that observed for the modulus. The trends in phase angle measurements shown in Figure 5 are in agreement with those shown schematically in Figure 1.

6.1.3. *Dissipated energy*

The dissipated energy per unit of volume ($\pi \sigma \varepsilon \sin(\varphi)$) is plotted versus number of loading cycles in Figure 6. In the same figure the surface temperature measured with a thermocouple mounted at the mid-height of the test specimen is plotted versus the number of loading cycles. The plotted data show how closely the specimen temperature is synchronized with the dissipation of energy within the specimen. This can be seen especially at the beginning of Stage II (self heating) and Stage III (self cooling). When the rate at which energy is dissipated becomes constant (Stage I and Stage III at the completion of self-cooling) the specimen temperature also becomes constant.

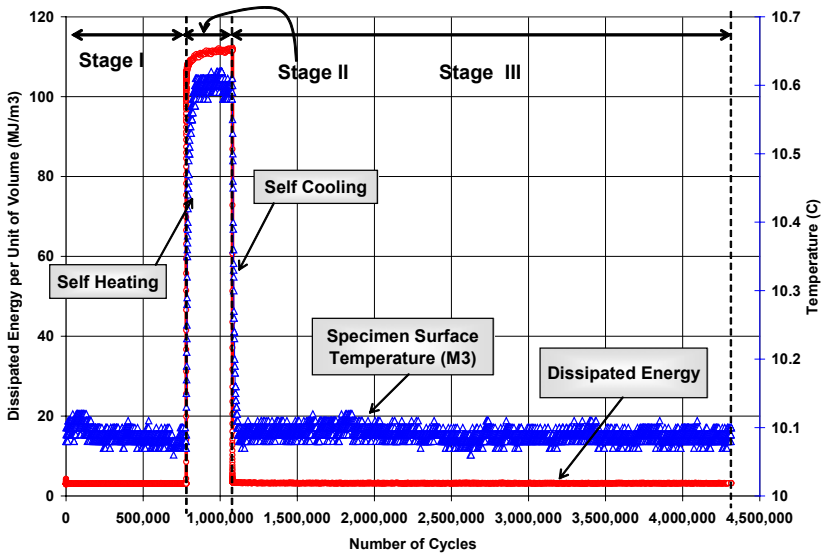

Figure 6. *Dissipated energy and self heating, I-80*

The calculated energy dissipated per cycle in Stage II is about 37 times more than that of Stage I or Stage III, Table 4. In Stage II the dissipated energy generates sufficient heat to raise the measured temperature of the specimen surface by approximately 0.5°C. Considering that the dissipated energy in Stage I or III is 37 times less than that of Stage II, by simple proportion the temperature rise on the specimen surface during Stages I or III should be approximately 0.01°C, too small to be reliably measured. This small temperature rise in Stage I explains why the effect of self heating on the drop of modulus is insignificant compared to the effect caused by thixotropy during Stage I.

6.1.4. *Specimen surface temperature*

Temperature was measured at nine points on the specimen surface (a thin, pressure-sensitive paper tape was used to keep the tip of the thermocouple in intimate contact with the specimen surface). Thermocouples were placed at mid-height adjacent to each displacement transducer (M1, M2 and M3) and at the ends of the specimen above (T1, T2 and T3) and below (B1, B2 and B3) each transducer. Temperature was also measured in the air adjacent to the test specimen. Temperature measurements are reported in Figure 7 and, with an expanded scale showing the self heating and self cooling regions, in Figure 8.

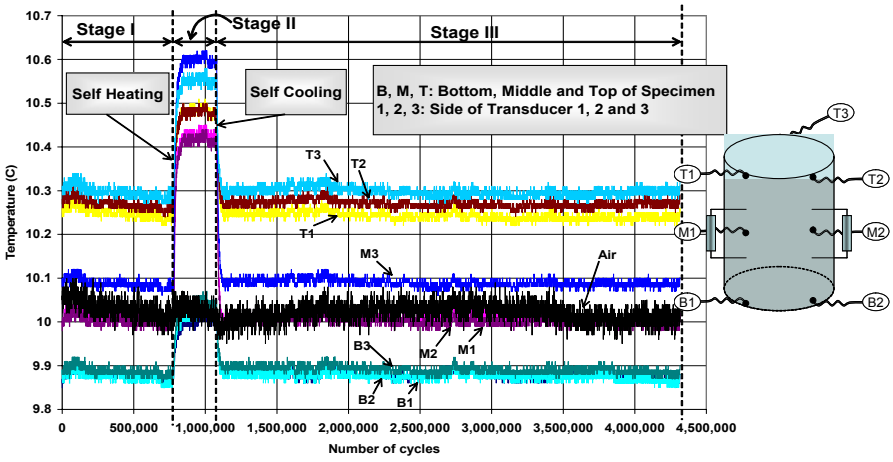

Figure 7. *Temperature measurement, I-80*

Heat transfer between the specimen and the upper aluminum platen was minimized with the addition of an insulative insert, resulting in a temperature difference of only 0.4°C between the top and bottom of the test specimen. Without the insert, heat was transferred from the hydraulic oil to the actuator and then through the load cell and the upper end cap to the test specimen. This caused as

much as a 4°C temperature differential between the top and bottom of the test specimen. The deviation of temperatures measured on the test specimen surface (7,200 data points per thermocouple in Figure 7) and in the environmental chamber air from their average was less than ± 0.015 and ± 0.03°C, respectively, during the test.

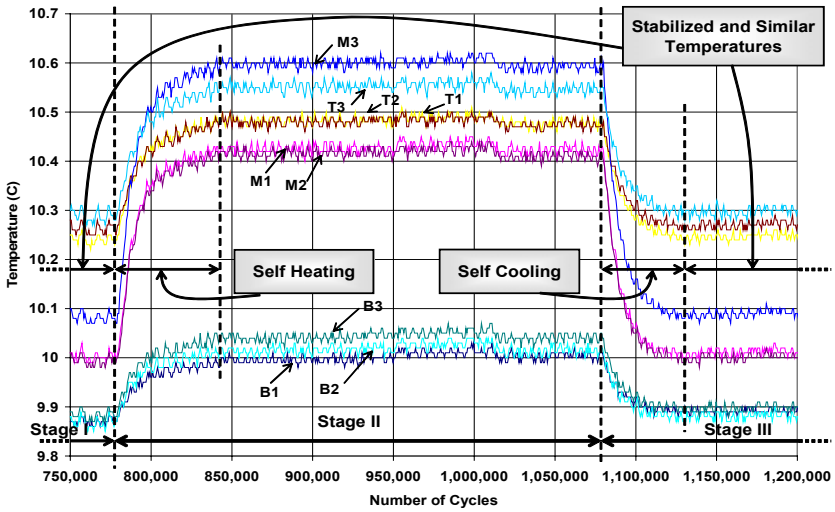

Figure 8. *Self heating and self cooling, expanded scale, I-80*

Observations based on Figure 8 show that the minimum temperature changes occur at the ends of the specimen where the heat is exchanged between the specimen and the aluminum end caps and where the strains in the specimen due to end restraint are lower than at the mid-height of the specimen. Self heating and self cooling occur at the beginning of Stage II and Stage III, respectively, and continue throughout both stages.

The maximum temperature change measured on the surface of the test specimen due to self heating or self cooling was approximately 0.5°C. Based on earlier work using a similar testing mode the maximum temperature change due to self heating at the center of the test specimen was estimated to be 1.0°C. The average temperature change within the specimen will then be approximately 0.75°C [ASH 98]. At 10°C and 10 Hz an increase of 1.0°C in the specimen temperature decreases the modulus by about six percent [ASH 98]. Therefore the decrease of modulus caused by self heating during Stage II is 4 to 5 percent for the I-80 test specimen. A similar analysis of the specimen temperature change during Stage I (< 0.01°C) indicates a very small decrease in modulus, approximately 0.1 percent. Figure 7 also shows that the temperature distribution within the specimen becomes less uniform during

fatigue loading, another reason for making displacement measurements in the mid-height of the specimen.

6.2. *Application of protocol to the AC-5 mixture*

In order to confirm the observations that were made for the I-80 test results, the protocol was applied to a second mixture. In general, the same trends were observed but the behavior was slightly different. A summary of the results for the AC-5 mixture is given in Table 5, and the variation of modulus and phase angle versus the number of loading cycles are shown in Figure 9.

Table 5. *Test results for AC-5 mixture*

	Initial	Stage I	Stage II	Stage III
Number of cycles	-- --	1,000,000	300,000	3,600,000
Strain during stage, μ-strain	17	17	89	17
Stress, end of stage, MPa	0.18[(a)]	0.11	0.51[(b)] 0.39	0.10
Modulus, end of stage, MPa	7,060[(a)]	6,480	4,410	6,290
Modulus change in stage, MPa	-- --	-580[(c)]	-2,070	1,880
Asymptote normalized slope	-- --	$2x10^{-9}$	-- --	$9x10^{-10}$
Phase angle, end of stage, °	25.0[(a)]	26.2	35.1	26.9
Dissip. energy/unit vol., MJ/m^3	6.0	3.1	68.0	2.4
Heating/Cooling, °C	0	0	0.3 to 0.4	-0.3 to -0.4

[(a)] At beginning of Stage I, [(b)] At beginning of Stage II, [(c)] Negative change means loss in property.

During Stage I the modulus decreased by more than 8 percent for the AC-5 mixture compared to 1.7 percent for the I-80 mixture. Additionally, a much larger number of cycles, approximately 500,000 compared to 50,000 for the I-80 mixture, is needed to reach an asymptote in Stage I. The drop in modulus and the number of cycles required to reach a definite asymptote are much larger for the AC-5 mixture than for the I-80 mixture, indicating that thixotropic behavior in the binder has a larger effect on the AC-5 mixture. Although the details are not reported here, the rheological behavior of the binders at the test temperature are very different given their PG grading. Further, the I-80 binder was polymer-modified whereas the AC-5 binder was unmodified. These factors may explain the difference in thixotropic behavior between the I-80 and the AC-5 mixtures.

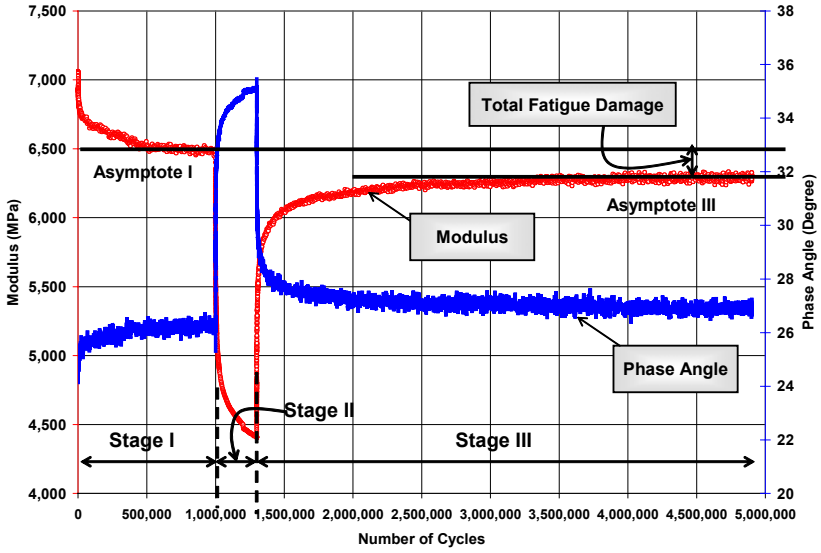

Figure 9. *Modulus* versus *number of loading cycles, AC-5*

6.3. *Summary of I-80 and AC-5 results in regard to fatigue*

The results of the analysis discussed above clearly demonstrate the presence of an endurance limit of at least 19 μ-strain and 17 μ-strain for the I-80 and AC-5 mixes, respectively. The change in modulus caused by thixotropy is calculated as the total change in modulus minus the change caused by the other effects, i.e. self heating, material nonlinearity, and fatigue, Table . For both mixes, after 300,000 loading cycles the percentage loss in modulus caused by fatigue is only 2.6 to 2.7 percent of the initial modulus. Self heating accounts for 3 to 5 percent of the initial modulus, and the effect of nonlinearity is 1 to 3 percent. The estimate for nonlinearity was obtained from the literature [DOU 95]. This leaves the remainder, thixotropy, as the major cause of modulus change. This is true when there is an increase in the loading amplitude as well as when the loading amplitude is decreased. The damage obtained by applying the protocol to the I-80 and AC-5 mixtures represents only 11 and 7 percent of the fatigue obtained by standard fatigue analysis where the fatigue damage is based on the change in modulus expressed as a percent of the initial modulus, Table . Since about 90 percent of the modulus decrease is caused by non-fatigue phenomena, the authors must conclude that standard testing and analysis provide a misleading estimate of the fatigue damage.

The initial modulus for the I-80 mixture (12,430 MPa) is much larger than that of the AC-5 mixture (7,060 MPa). Since both mixtures show similar damage

percentage for the same loading in strain-controlled mode, at 10°C the I-80 mixture is much more fatigue resistant than the AC-5 mixture.

Table 6. *Share of modulus drop for I-80 and AC-5*

Cause of change	Changes in modulus, percentage			
	Expressed as a percent of initial modulus		Expressed as a percent of total loss in modulus	
	I-80	AC-5	I-80	AC-5
Total change	24	38	100	100
Due to fatigue	2.6	2.7	11	7
Due to self heating	4-5	3-4	17-21	8-11
Due to nonlinearity	1-3	1-3	4-12	3-8
Due to thixotropy	13-16	28-31	56-68	74-82

7. Further consideration of self healing and thixotropy

The increase in specimen modulus that occurred during Stage III of the proposed protocol is counterintuitive. This is especially true considering the fatigue damage incurred during Stage II. In order to further investigate this phenomenon and its relationship with healing and thixotropy, a modified form of the proposed protocol was applied to a specimen prepared with Rt.15 mixture.

7.1. *Background*

An increase in the modulus of the test specimen following a rest period has been documented in the literature by a number of researchers [ASH 98, BAA 04, BOD 03, BON 82, BRE 05, LIT 99, PRO 97, RIV 97]. Nevertheless, not all studies conclude that this increase in modulus is of benefit with respect to the healing of fatigue damage. In addition, there is no agreement as to whether self healing occurs only during the rest period or whether self healing and fatigue damage can occur simultaneously.

Little *et al.* presumed that the fatigue process is a result of the competing processes of crack growth and crack healing. Furthermore, they presumed that fatigue is a two-stage process, a) microcrack growth and healing and b) macrocrack growth and healing, and that both stages are governed by the same principles [LIT 99]. Carpenter *et al*. studied the existence of an endurance limit. In order to explain the appearance of an asymptote after an initial decrease in modulus they hypothesized that the repair process is continual and occurs to some extent even

during loading [CAR 03]. Pronk carried out a fatigue test with 10,000 cycles at 160 μ-strain and observed a continuous increase in the modulus during the next 2,000 cycles when the applied strain was reduced to 40 μ-strain. He interpreted the increase in modulus as being the result of self healing and concluded that healing occurs simultaneously with fatigue damage [PRO 97]. The experiment performed by Carpenter *et al.* was similar to Stage I of the proposed protocol, and the experiment performed by Pronk was similar to Stages II and III.

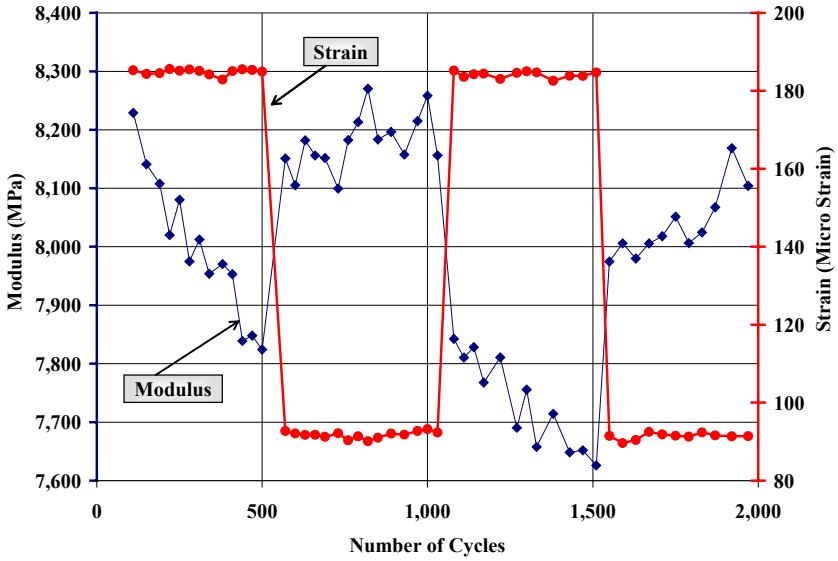

Figure 10. *Changes in modulus with change in strain amplitude [ASH 98]*

Rivière applied two different fatigue loading patterns: a rest period between each of two successive loading cycles and another pattern where the rest periods were replaced by a few cycles at low strain. Supposedly the latter pattern did not cause any damage to the specimen and at the same time restrained any self healing in the specimen. Rivière concluded that in regard to fatigue life, both loadings yielded similar results [RIV 97].

Ashayer applied different combinations of loading to study the modulus increase that occurs when the amplitude of the applied load is reduced (but not to zero) during fatigue testing. An example is given in Figure 10 where 500 cycles of loading are repeated at strain amplitudes of 180 and 90 μ-strain. This figure shows that any decrease (increase) in the applied loading results in an immediate and continuous increase (decrease) in the modulus. In this study it was concluded that the rapid and relatively large increase in modulus during the rest periods, or when the loading

amplitude is reduced, cannot be the result of self healing or self cooling alone [ASH 98].

7.2. *Test description and discussion*

The proposed protocol with some modifications was applied to the Rt.15 specimen. A plot of the modulus versus the number of cycles is presented in Figure 11: Stage I (840,000 cycles at 19 μ-strain), Stage II (230,000 cycles at 100 μ-strain) and Stage III (1,600,000 cycles at 18 μ-strain). For this test Stage II was allowed to proceed until Phase III fatigue was observed. Of the 230,000 loading cycles applied during Stage II, Phase III fatigue was observed during the last 90,000 cycles (appearance of Phase III was verified with the results of strains obtained from transducers 2 and 3). Despite the presence of Phase III fatigue at the end of Stage II, the modulus increased at the start of Stage III, recovered more than 90 percent of its loss, and reached a well defined asymptote at the end of Stage III. Once an asymptote was reached the loading was applied for more than 500,000 cycles to be certain that no additional recovery would take place. At point D shown in Figure 11 the strain amplitude was increased to 100 μ-strain, the same as Stage II. Despite the near complete recovery of the modulus, the specimen life in the last loading stage was very short and complete rupture of the test specimen occurred after only 30,000 cycles of loading. The moduli at points B (cycle number six in Stage II) and D (cycle number one in Stage III) in Figure 11 are equal. If the modulus is indicative of the amount of fatigue damage that the specimen has sustained the fatigue behavior after point D should be similar to that observed after point B. This certainly is not the case. One conclusion seems certain; the 90 percent increase in modulus that occurred during Stage III cannot be equated to 90 percent healing given the short life of the specimen in the last stage of loading. Therefore, it appears that the increase in modulus cannot be attributed to healing alone. Further, modulus when taken alone is not indicative of damage incurred during previous loading cycles, or remaining fatigue life.

Consideration of the change in modulus that occurs at the beginning of a fatigue test, at the beginning of a rest period, or after a change in loading amplitude is usually neglected in the literature. Figure 12 presents the modulus decrease and increase for all the first 100 cycles (10 seconds) of Stage II and Stage III for the Rt.15 specimen. In Stage III, the recovery of modulus after 1 second is about 6 percent of the initial modulus and 10 percent after 10 seconds of loading. None of the phenomena such as non-linearity (shifting from 100 to 20 μ-strain), self cooling, or transient effects can explain this rapid and relatively large increase in modulus. The authors also find that it is difficult to accept that the mixture can self heal its cracks at this speed while still being loaded at a relative low temperature of 10°C.

It should also be emphasized that this fast and relatively large increase in modulus is not exclusive to the Rt.15 test specimen, as it was observed for the other

specimens tested in this study and in studies by others [ASH 98, PRO 97]. A large part of this recovery, which the authors have chosen to call thixotropy, may occur at the molecular or macromolecular level. The authors suspect that much of what they attribute to thixotropy may be the result of unexplained restructuring of the asphalt binder at the molecular level (molecule interaction) as opposed to microcracking.

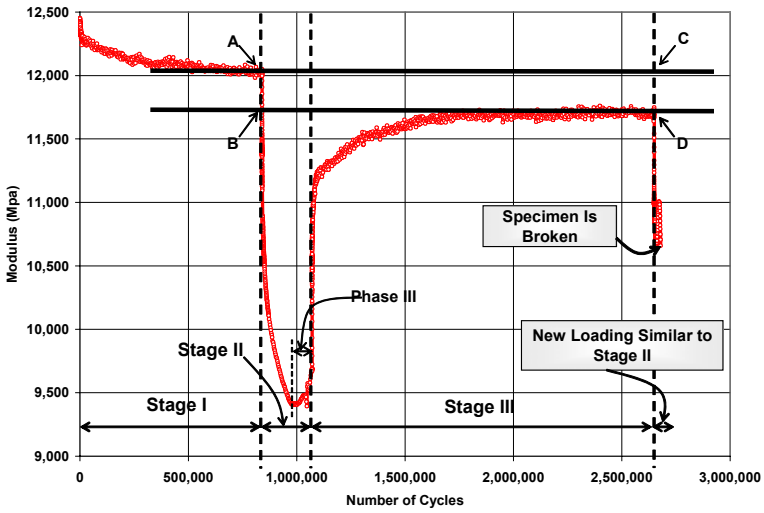

Figure 11. *Modulus* versus *number of loading cycles, Rt.15*

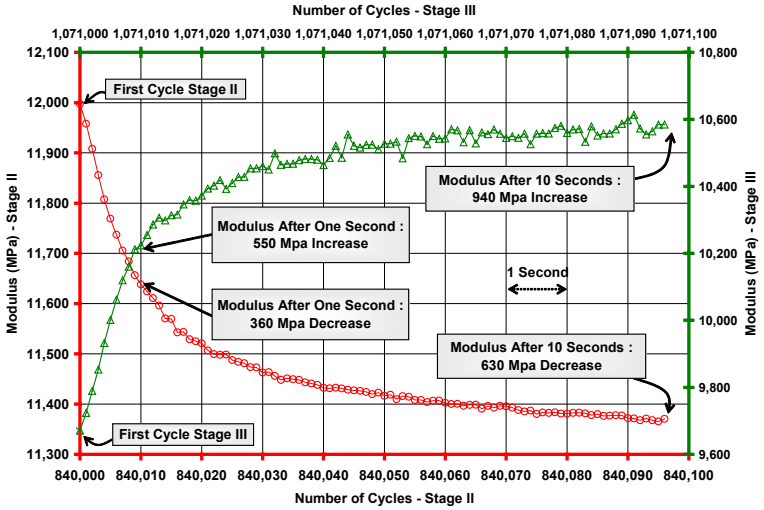

Figure 12. *Modulus at the first 100 cycles (10 seconds) of stages II and III, Rt.15*

7.3. *Thixotropy*

The effect of thixotropic behavior is observed when the loading is both increased (the effect is a decrease in modulus) and decreased (the effect is increase in modulus). The effect of thixotropic behavior on modulus is greater when the load amplitude is first changed (increase or decrease) and diminishes exponentially as the loading proceeds. If cycles of constant strain amplitude are applied for a sufficient duration of time, the modulus converges to a constant equilibrium value. The changes in modulus caused by thixotropic behavior appear to be dependent on the magnitude of the change in the load. Further study is needed to define thixotropy load and time dependency.

7.4. *Coexistence of fatigue and healing*

If the fatigue process is the result of simultaneous crack growth and healing as advanced by other researchers the behavior resulting from the proposed protocol may be interpreted in the following manner:

Stage I: When the loading is first initiated crack growth dominates the process and causes the modulus to decrease. Crack growth and healing occur simultaneously and after some number of cycles crack growth is offset by crack healing. At this point an asymptote, which represents a balance between microcracking and healing, is reached.

Stage II: Fatigue damage is incurred during Stage II where the rate of healing is not sufficient to compensate for the rate of microcracking.

Stage III: With the reduction in loading at the beginning of Stage III, crack healing dominates the process and causes the modulus to increase. Crack growth and healing occur simultaneously and after some number of cycles crack healing is offset by crack growth. At this point another asymptote, which again represents a balance between microcracking and healing, is reached.

Fatigue damage: The difference between the moduli of the two asymptotes is sole the result of fatigue damage incurred in Stage II.

Within this context, if all of the damage is attributed to microcracking, the microcracks may be divided in two categories. The first category includes microcracks that self heal when the amplitude of loading is decreased. The second category of microcracks do not self heal when the amplitude of loading is decreased, and these are the microcracks that cause the fatigue damage. Therefore, from this point of view, thixotropy may be defined as a reversible behavior in which microcracks form when a loading is applied and self heal with the decrease in the loading.

Whether thixotropy is the result of restructuring at the molecular or macromolecular level, the result of simultaneous microcracking and healing, some

other phenomena, or a combination thereof, the proposed protocol presented in this paper isolates its effects as well as the effects of other non-fatigue related phenomena. The effect of thixotropic behavior was quantified in this paper, and it was shown that it has by far the major effect on the modulus changes during fatigue loading as well as during the rest periods or decreases in the loading amplitude. Therefore, thixotropy of HMAC should be a continuing subject of future research.

8. Summary and conclusions

A rigorous analysis of the fatigue process is greatly facilitated with a homogeneous test, in which the stress and strain and temperature distribution within the specimen are uniform. In addition to a homogeneous test, precise control of loading and temperature and precise measurements are necessary to conduct tests below the endurance limit and to reliably identify the effects of fatigue and non-fatigue phenomena. In this study, axial sinusoidal "push-pull" fatigue testing was conducted on cylindrical HMAC mixtures at 10°C and 10 Hz. The purpose of the study was to evaluate a new fatigue protocol with three successive stages of loading. A number of phenomena that are not related to fatigue, such as self heating, self cooling, material nonlinearity, and thixotropy, contribute to the changes in modulus that are observed during a fatigue test. The proposed protocol separates the effect of fatigue damage on the modulus from the effects of non-fatigue related phenomena. The specimen modulus is the only mechanical property that is required to determine the fatigue damage.

Based on the materials, testing protocol, and test results presented in this paper a number of conclusions are warranted:

A new protocol for quantifying the "true" fatigue damage without the need for complicated modeling or analysis was demonstrated successfully. Further studies are needed to validate the protocol on a large selection of mixtures and testing conditions.

Experimental evidence presented in this paper and by others in the published literature strongly suggests that HMAC can exhibit an endurance limit. Although the existence of an endurance limit was not conclusively demonstrated (which requires testing with hundreds of millions of loading cycles), it was shown that over a long period of loading at least an amplitude of strain exists during which the rate of fatigue damage is almost nil and that this rate decreases with the number of cycles.

Non-fatigue-related phenomena dominate the change in modulus in a fatigue test. An analysis of the data confirms previous conclusions by the authors and by others that the large and relatively sudden changes in the modulus that occur during the rest period, or during periods when the loading is decreased, cannot be entirely explained by self cooling or self healing.

The majority of the loss in modulus that occurs during a fatigue test is due to a reversible phenomenon that the authors refer to as thixotropy. Thixotropy is responsible for the greatest part of the time dependent change in modulus during loading as well as during rest periods or periods during which the loading is decreased. In Stage I of the proposed protocol thixotropic behavior can be experimentally quantified as long as the strain amplitude is below the endurance limit.

The specimen modulus alone, without further analysis, is not representative of the damage that has occurred during the specimen's prior loading history, nor is it representative of the specimen's remaining life.

The fatigue damage calculated from a standard fatigue analysis, where damage is computed on the basis of modulus change alone without the consideration of non-fatigue related phenomena, is seriously over-predicted. For the materials and loading conditions used in this study, the proposed protocol resulted in damage that was approximately an order of magnitude less than the damage that would be estimated from a standard analysis. Based on this finding, the authors question the reliability of standard fatigue testing and analysis.

Acknowledgments

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